Sofia University St. Kliment Ohridski

Overview of Femtoscopic Studies in Small Collision Systems

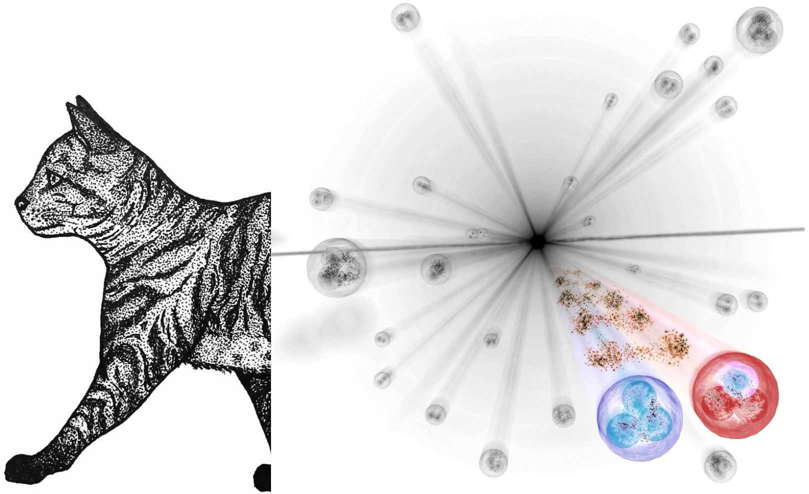
Dimitar Mihaylov

17th Workshop on Particle Correlations and Femtoscopy

4th November 2024, Toulouse

Part 1: The emission source in small systems

Dimitar Mihaylov



17th Workshop on Particle Correlations and Femtoscopy
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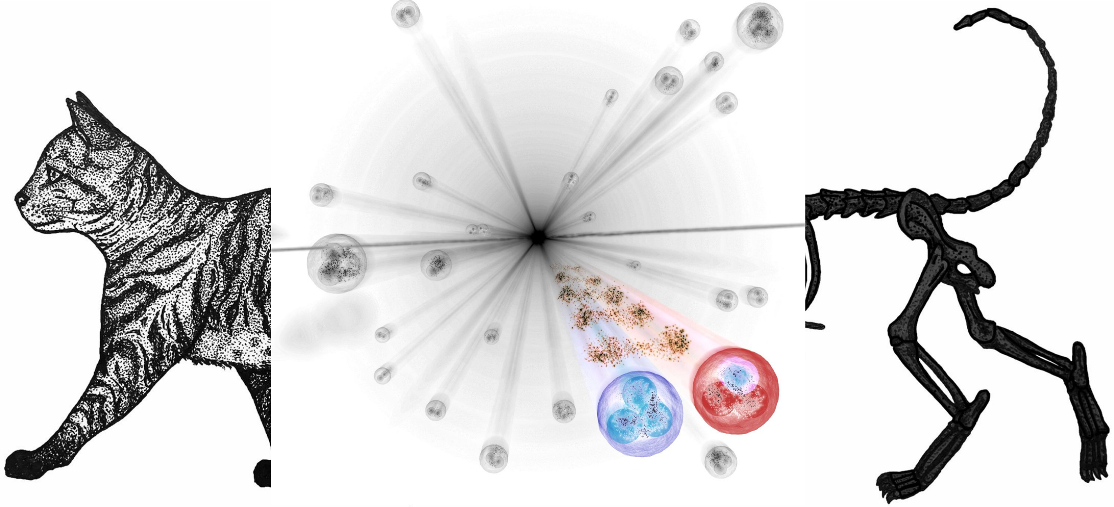
Part 2: Connecting femtoscopy and coalescence

Dimitar Mihaylov



17th Workshop on Particle Correlations and Femtoscopy

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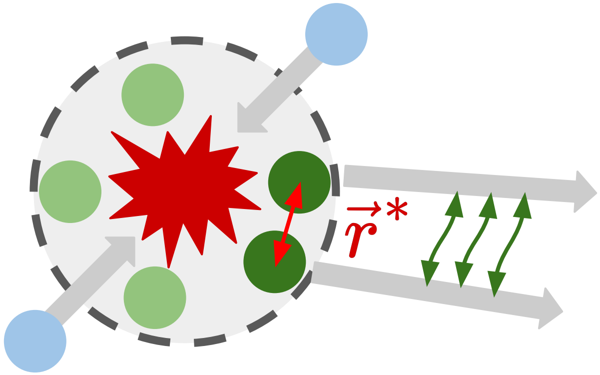
Femtoscopy @ LHC

Koonin-Pratt equation

[*Lisa et al.*](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



two-particle relative momentum
*q = 2 · k**

$\Psi(\vec{k}^*, \vec{r}^*)$
two-particle wave function

$$C(k^*) = \frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)} = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

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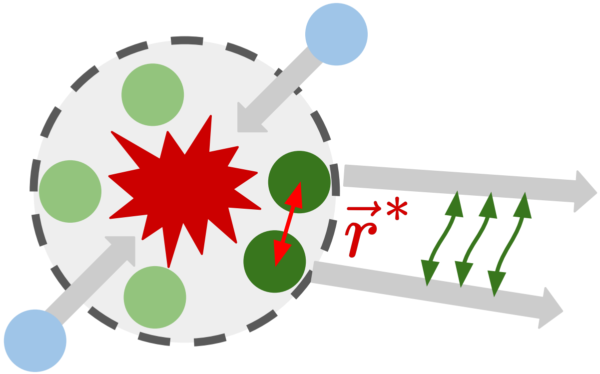

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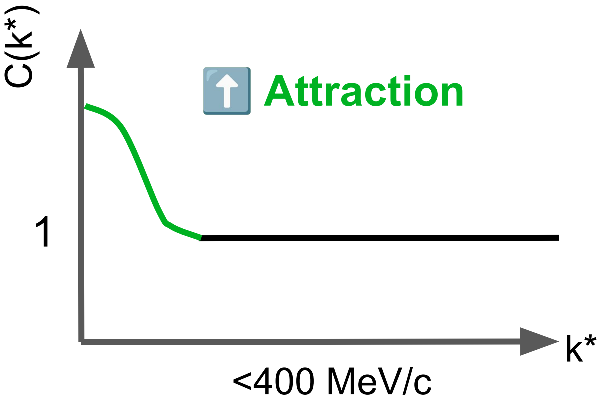

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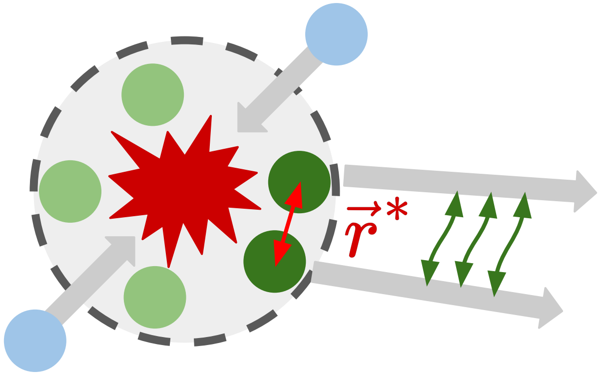

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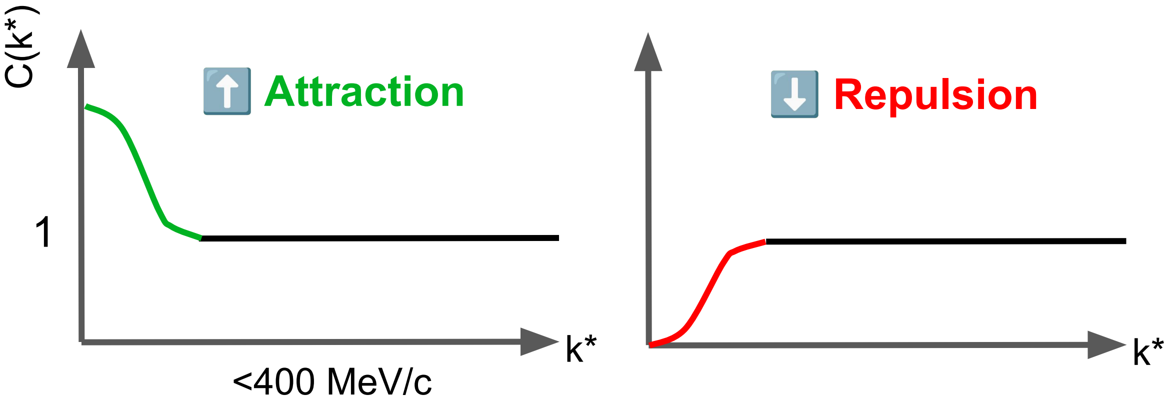

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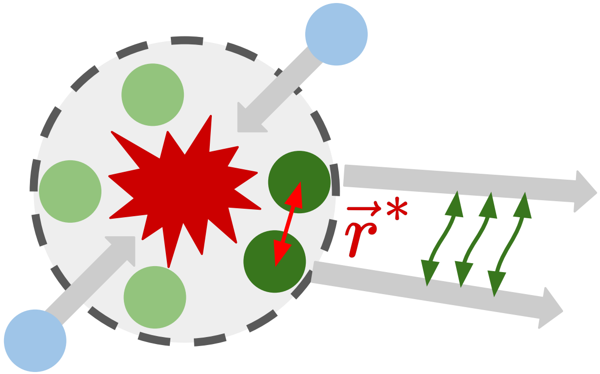

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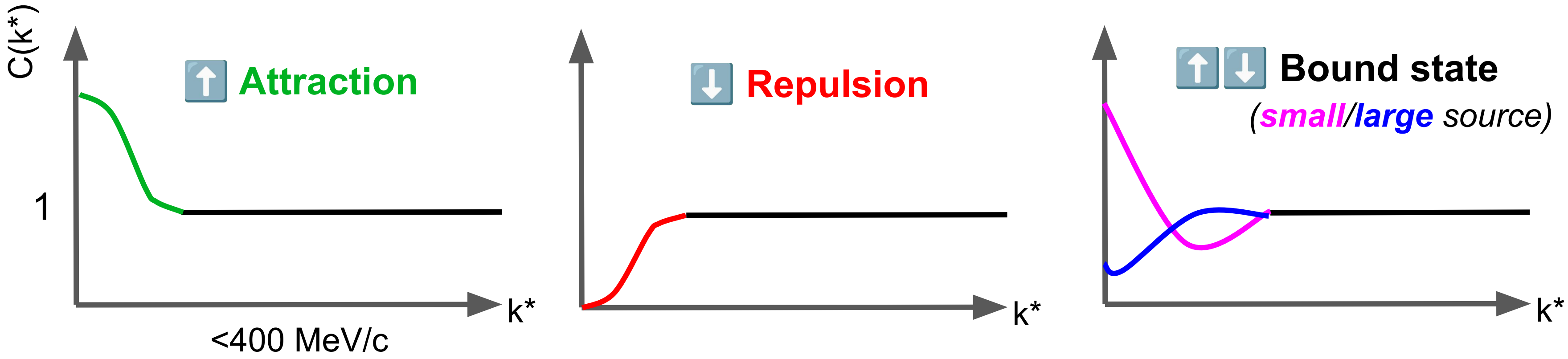

Femtoscopy @ LHC

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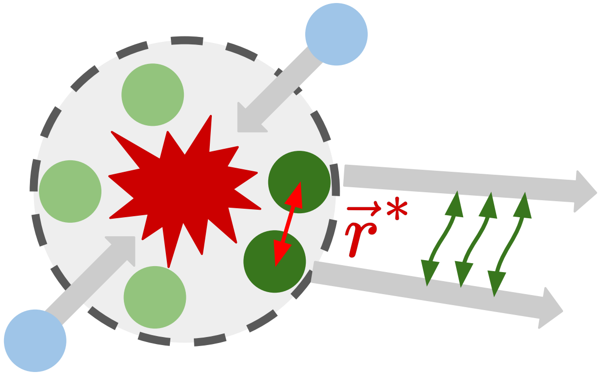

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Measure

Study the strong interaction

FIX

Femtoscopy @ LHC

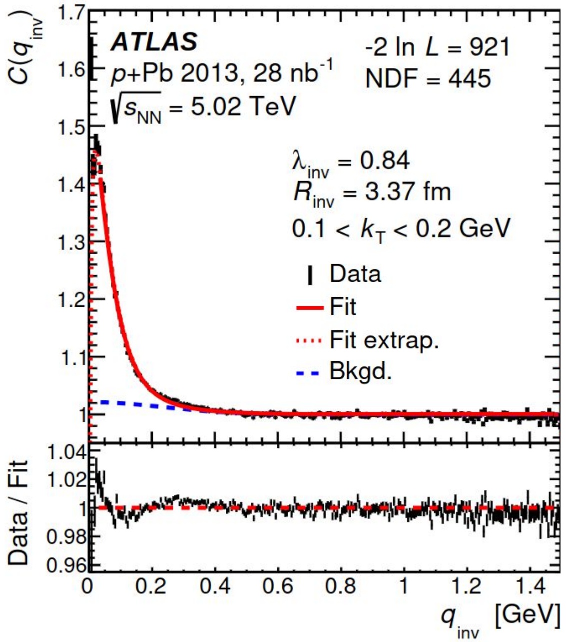
ππ correlations

ATLAS EXPERIMENT

p-Pb collisions @ 5.02 TeV

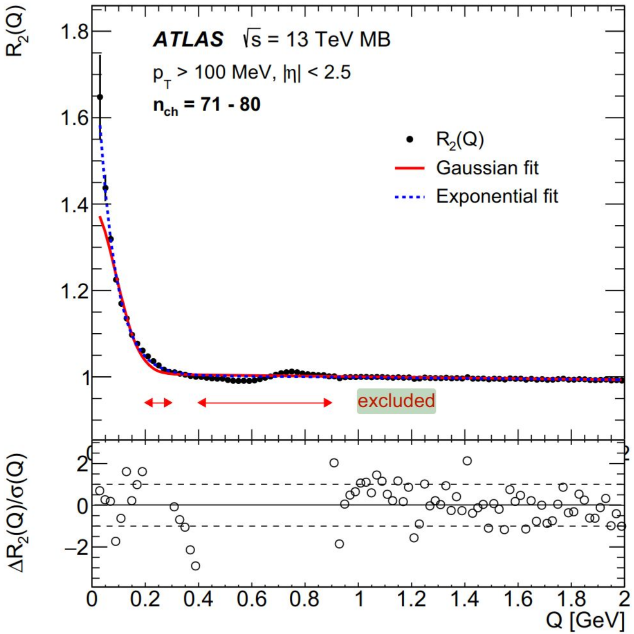
20-30% centrality

PRC 96 (2017) 6, 064908



pp collisions @ 13 TeV

EPJC 82 (2022) 7, 608



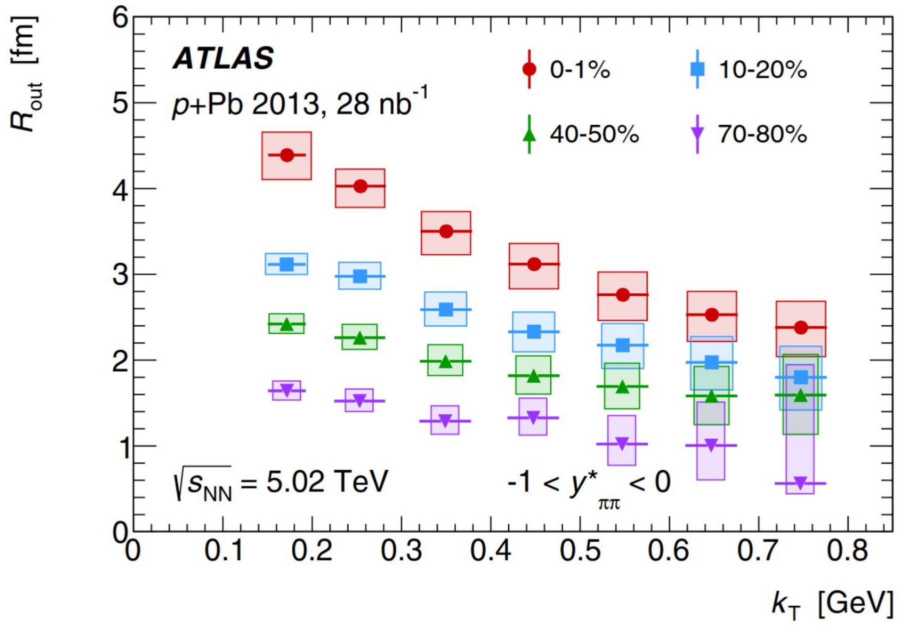
- **ππ correlations well described by a Cauchy source** (exp. correlation) in small coll. systems
- Also measured by *CMS* JHEP 03 (2020) 014 *LHCb* JHEP 12 (2017) 025
- Equivalent studies and use of Lévy distribution in HI collisions by *CMS* PRC 109 (2024) 2
- **The non-Gaussian profile (in small systems) may be related to production from resonances**

Femtoscopy @ LHC
Emission source

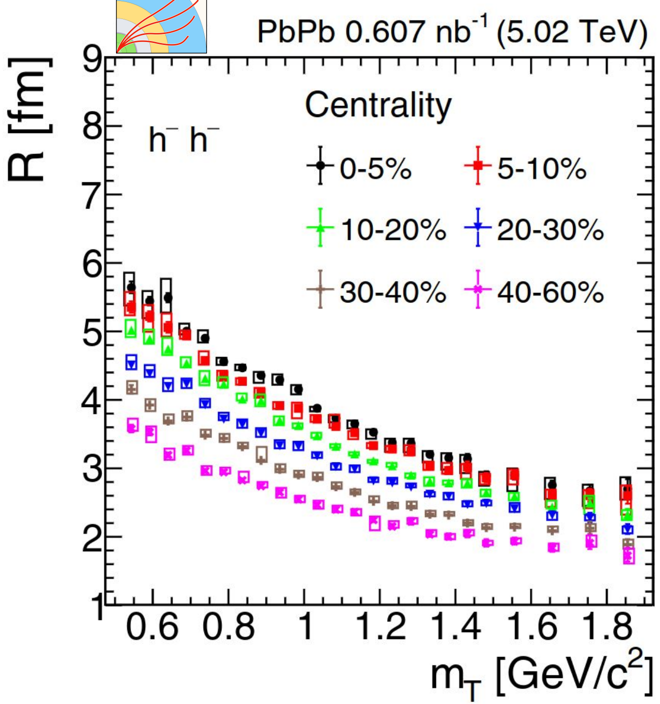
- k_T (m_T) scaling observed in p-Pb and Pb-Pb collision and associated with collectivity

p-Pb collisions @ 5.02 TeV

PRC 96 (2017) 6, 064908

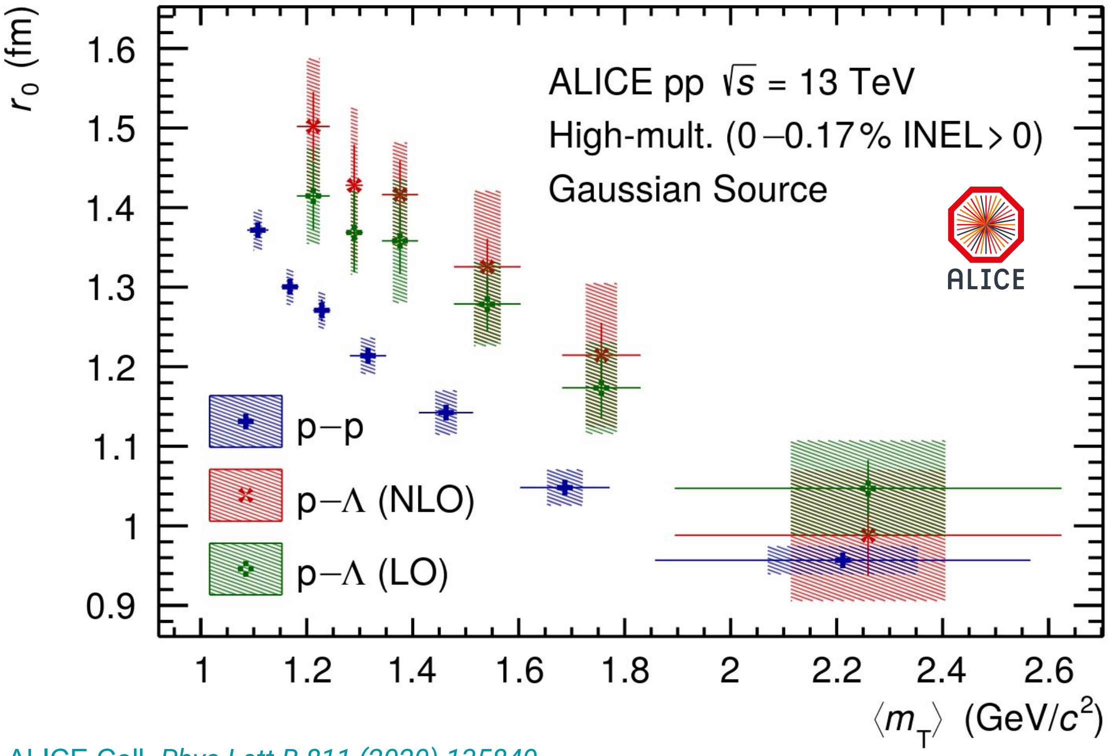


PRC 109 (2024) 2



Femtoscopy @ ALICE

In small collision systems (pp)



- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.

[ALICE Coll. *Phys.Lett.B 811 (2020) 135849*]

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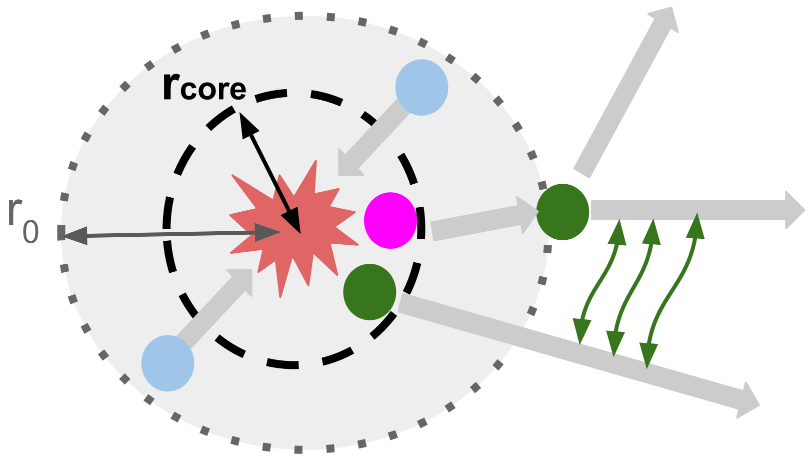

- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.
- **A hypothesis:**

  Gaussian “primordial core” **common for all species** modified by decays of short lived resonances.

  Based on statistical hadronization model ⅔ of all protons and Λs are produced like that. Resonances decaying into Λs, on average, live longer.
  <cτ> for protons c.a. 1.7 fm/c
  <cτ> for Λs c.a. 4.7 fm/c

Based on [ALICE Coll. *Phys.Lett.B 811 (2020) 135849*]

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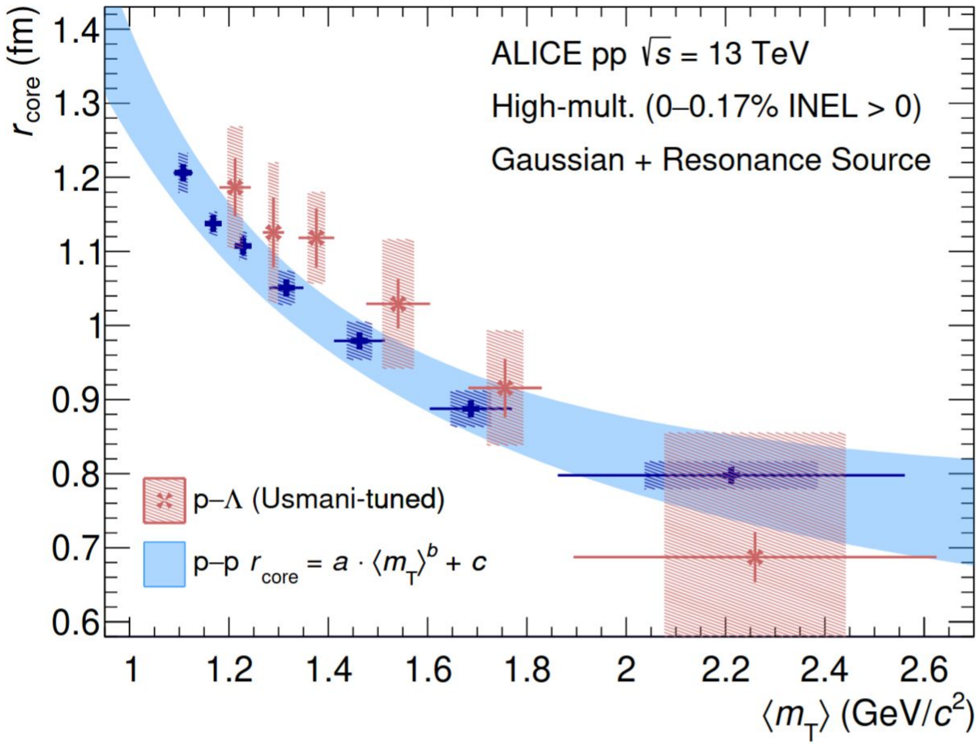


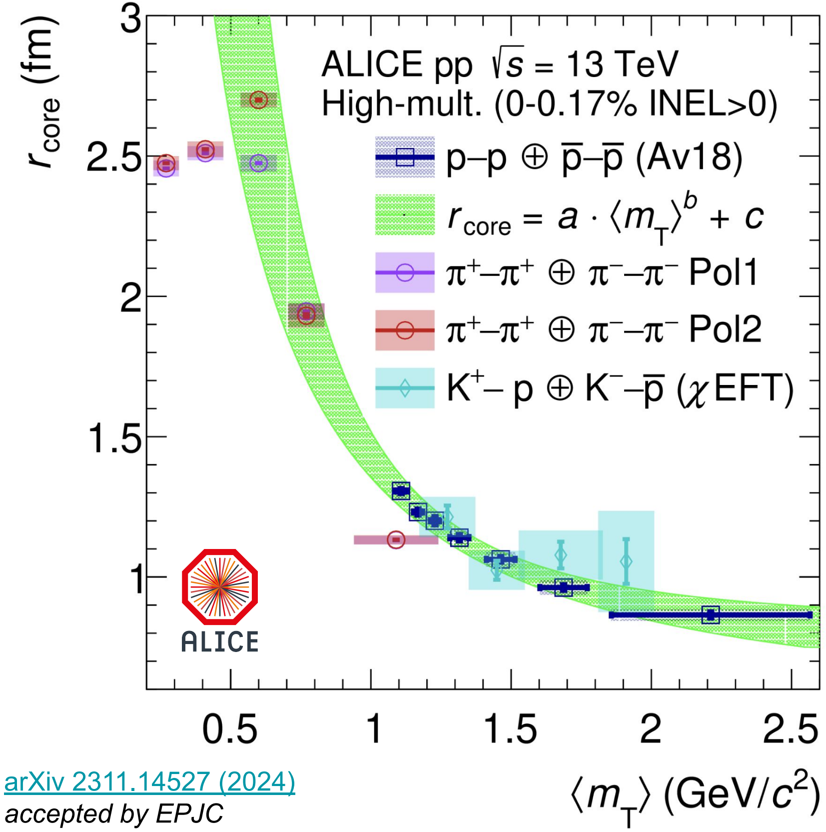
Based on [ALICE Coll. *Phys.Lett.B 811 (2020) 135849*]

- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.
- The **breakthrough** of the Resonance Source Model (RSM)
  A “primordial core” **common for all species** modified by decays of short lived resonances.

- Any baryon-baryon pair will follow this scaling, and the source size can be extracted based on the <mT> of the measured pairs!
- This allows for **precision studies of the strong interaction**.

Femtoscopy @ ALICE

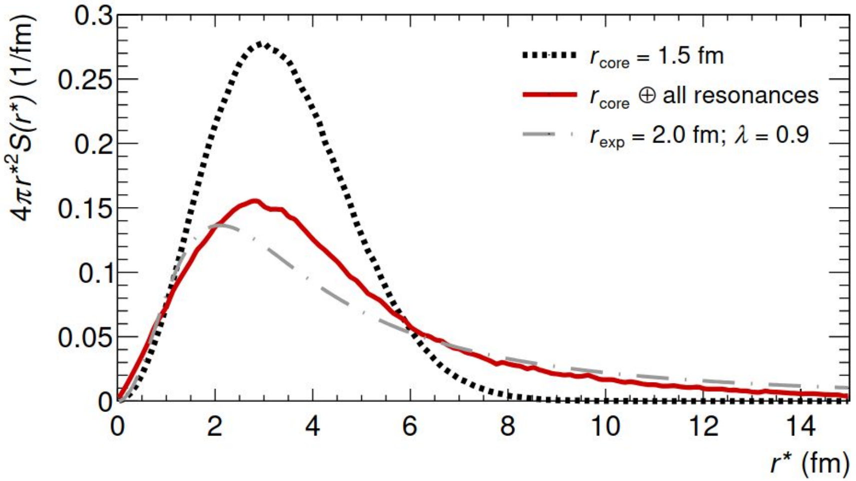
In small collision systems (pp)



[arXiv 2311.14527 (2024)](https://arxiv.org/abs/2311.14527)

accepted by EPJC

- The validity extended to mesons!
- The Cauchy ππ source explained by the combination of Gaussian core + short lived resonances.



Femtoscopy @ ALICE

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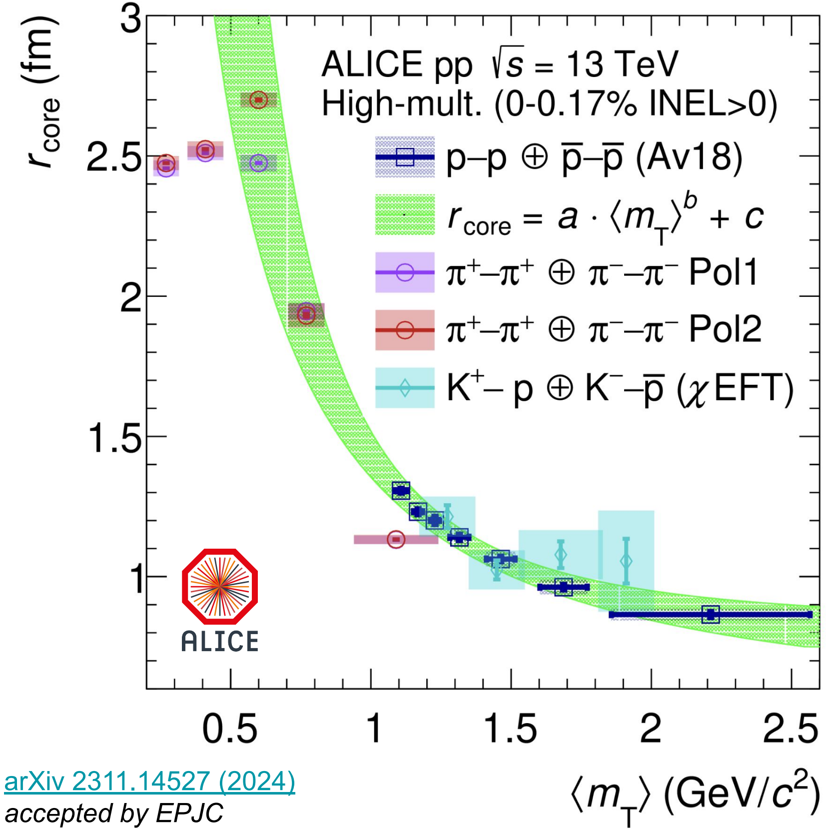

arXiv 2311.14527 (2024)
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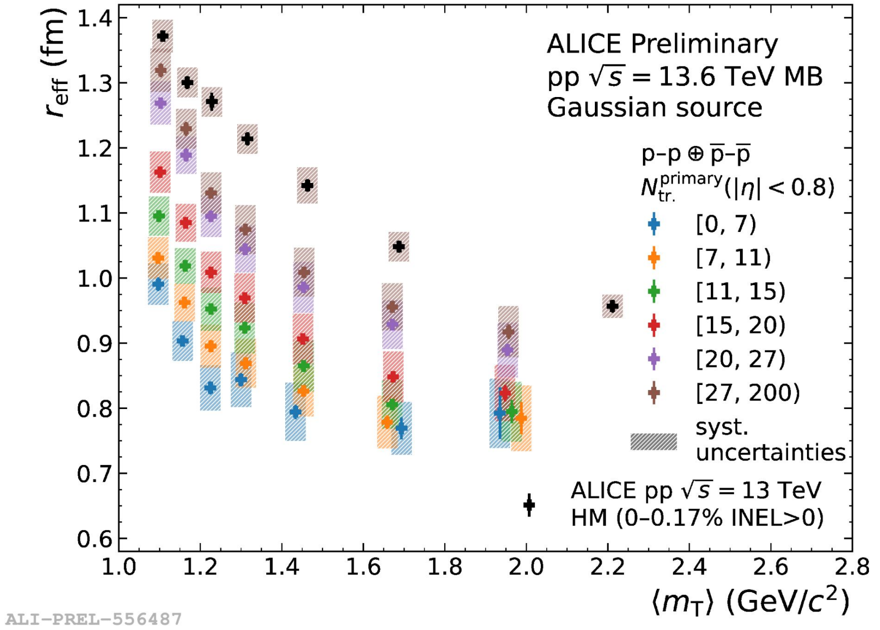
New RUN3 results for pp correlations in pp collisions at 13.6 TeV

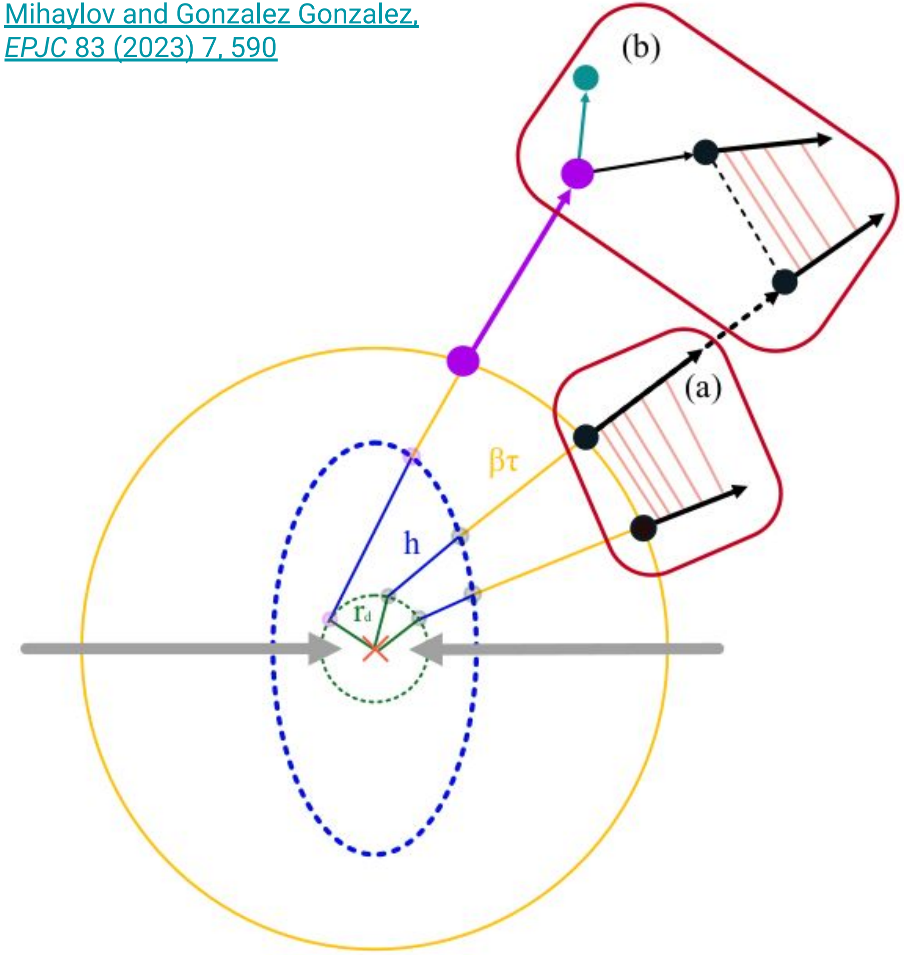


The CECA model

A generalization of the RSM

- MC simulation of single particles and resonances.

Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590



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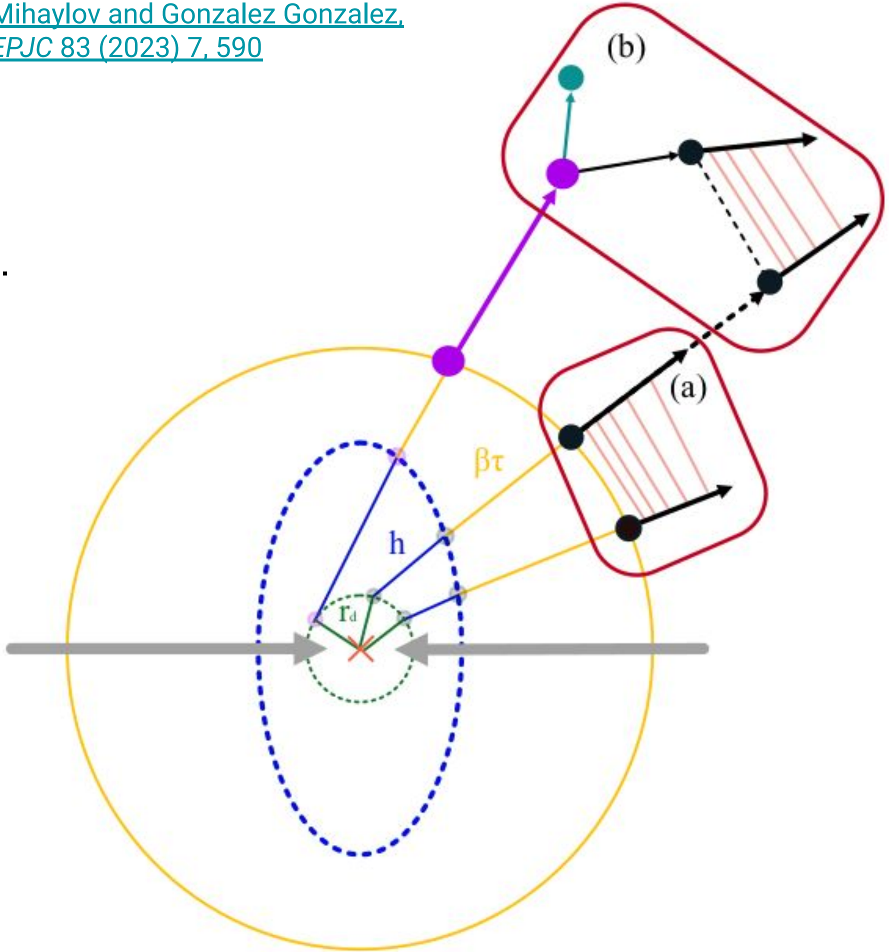
- MC simulation of single particles and resonances.
- Assume a common ellipsoidal ‘hadronization surface’. The latter serves as a source of spatial-momentum correlations, leading to mT scaling.



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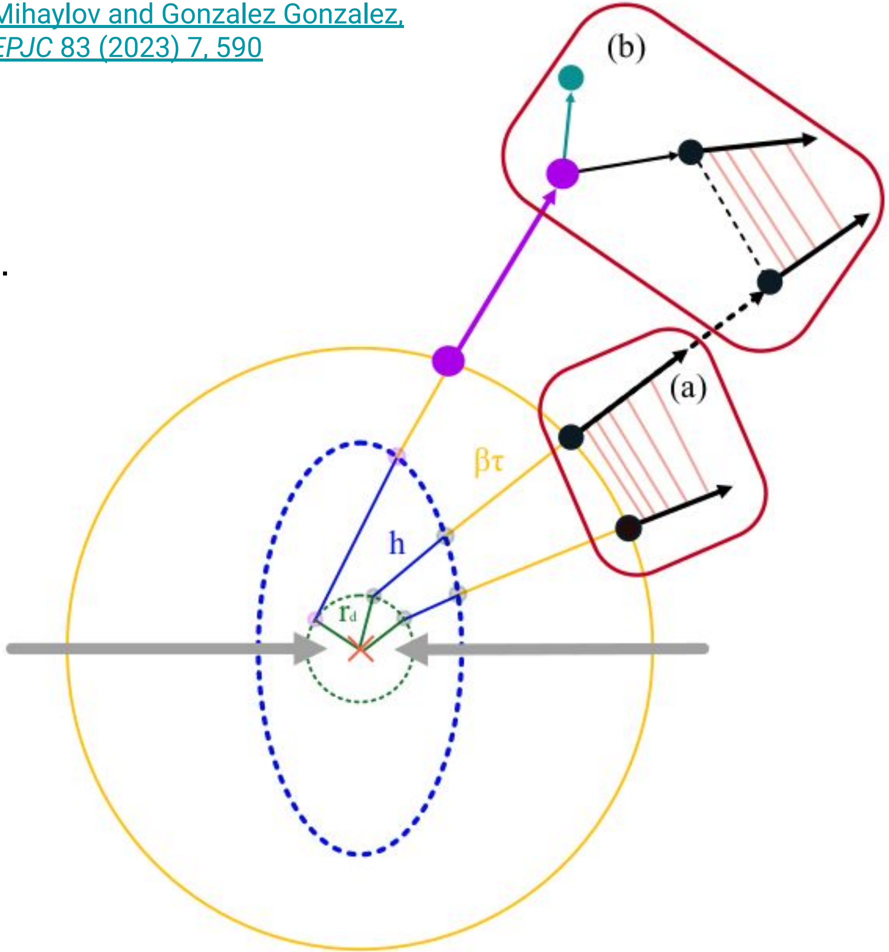
- Decay the resonances and form pairs, extract the corresponding 2- and N-particle source.



The CECA model

The resulting pp source

[Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590]

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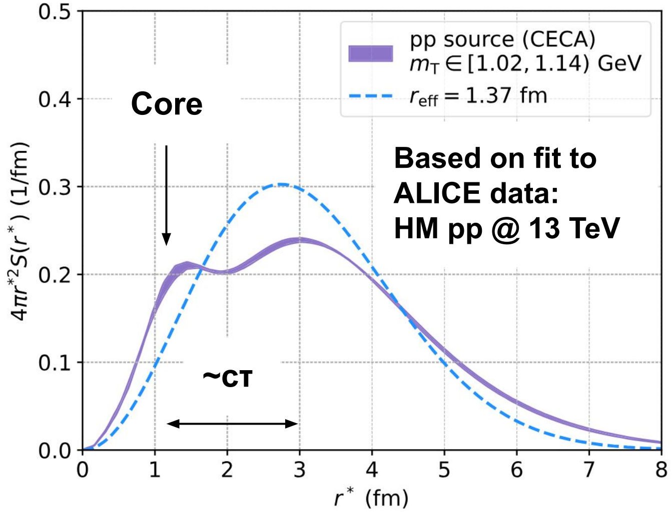
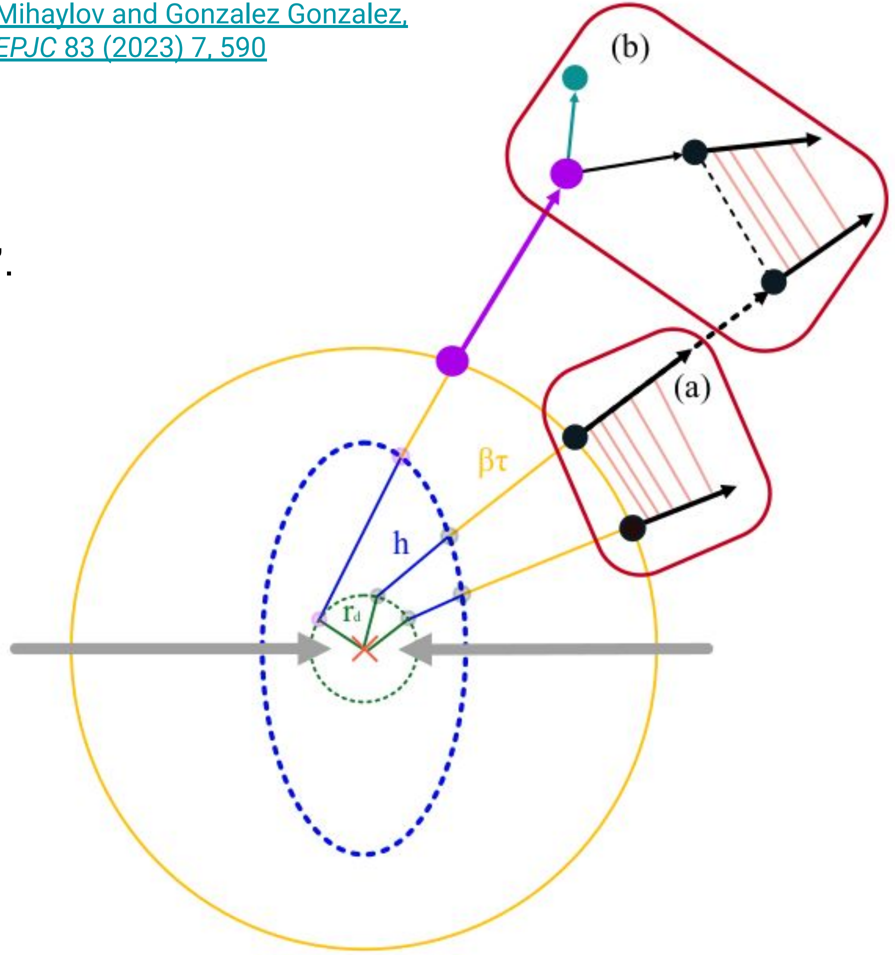
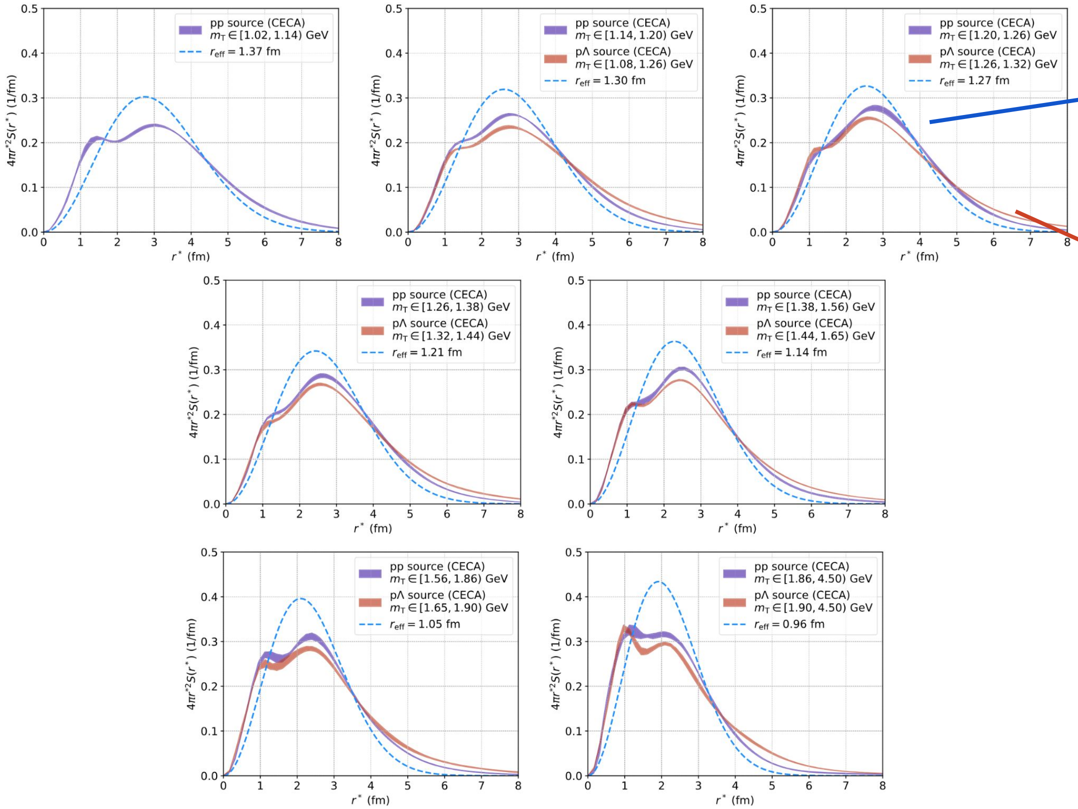




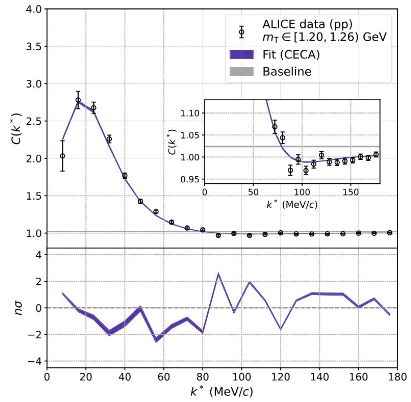
The CECA model

Simultaneous fit of pp and pΛ

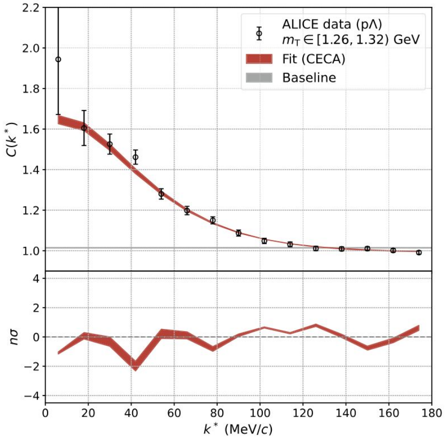
[Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590]



pp

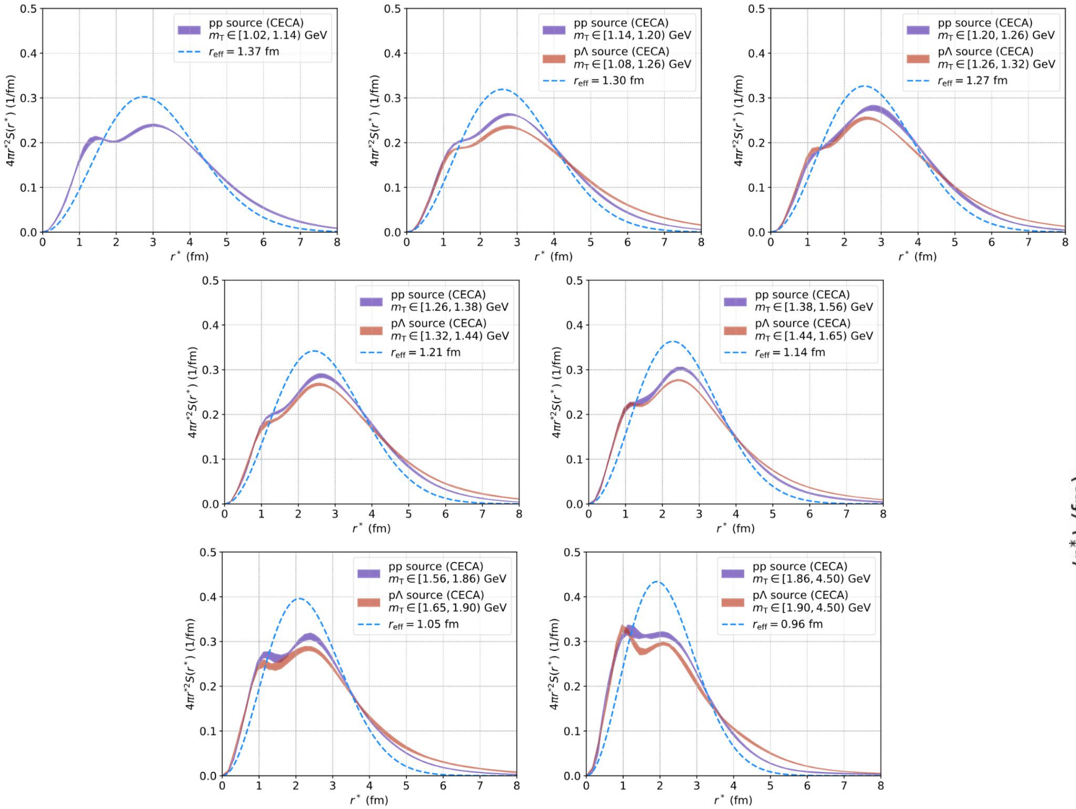


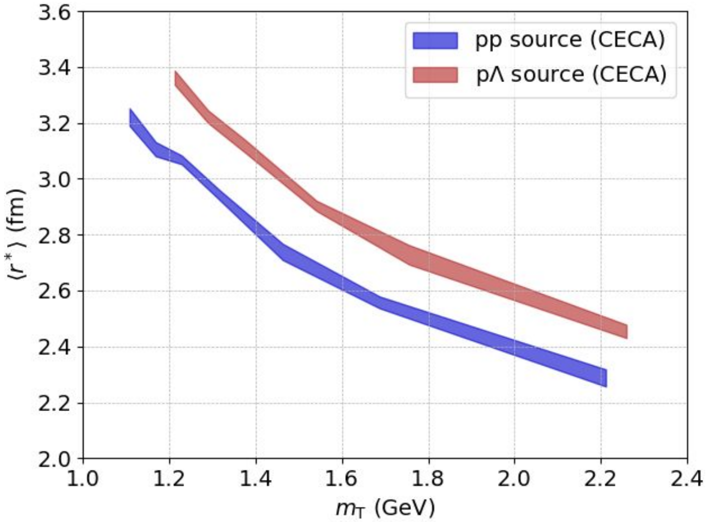
pΛ



The CECA model

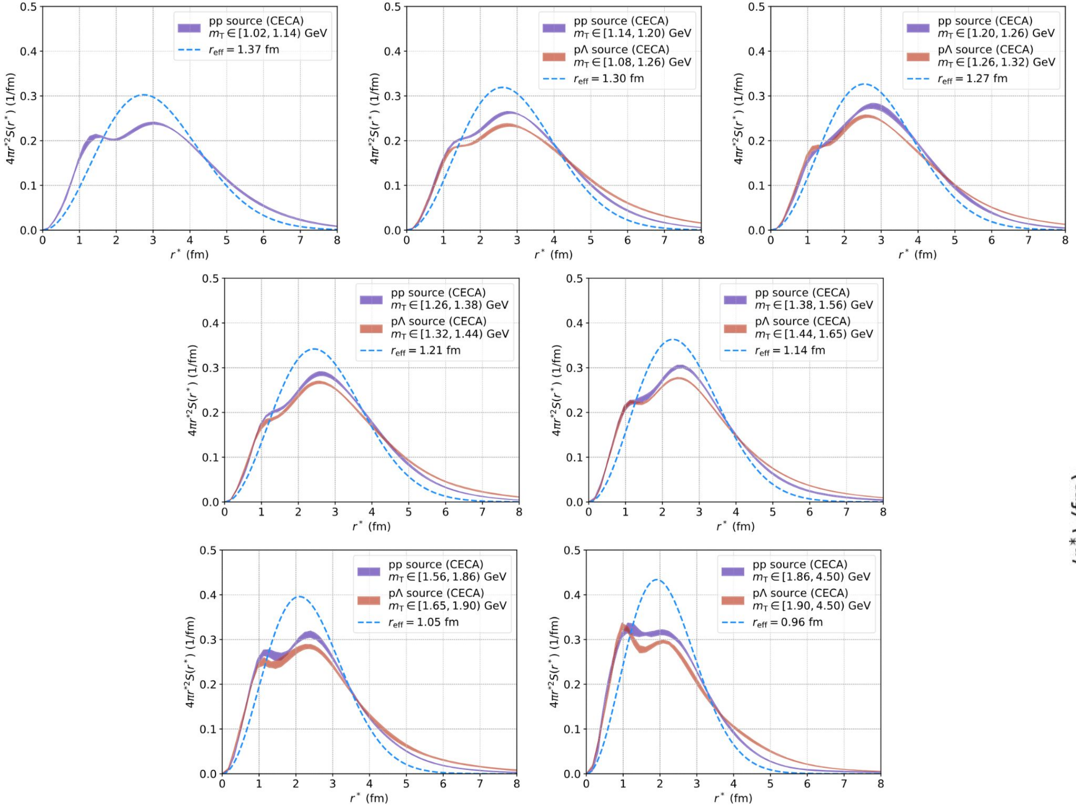
A generic mT scaling

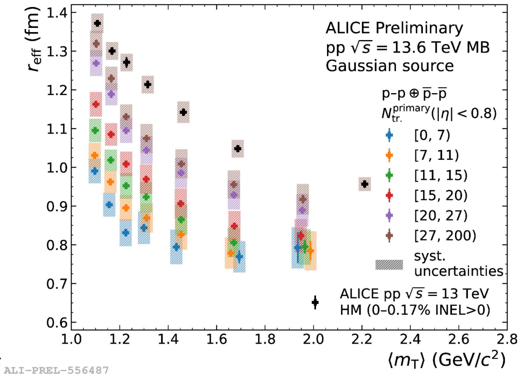


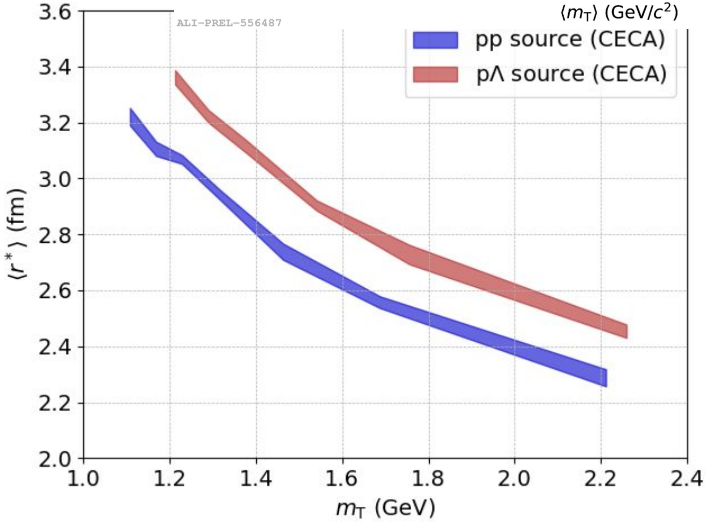


The CECA model

An open question: Can we reproduce the saturation of the ALICE RUN3 data?







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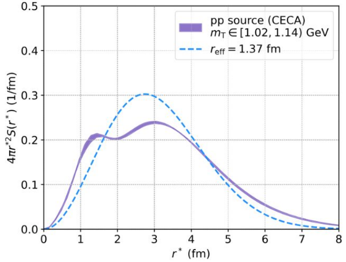
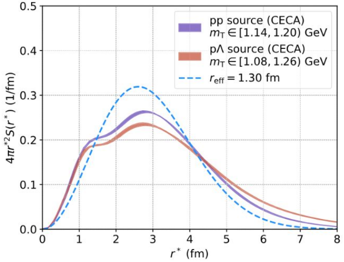
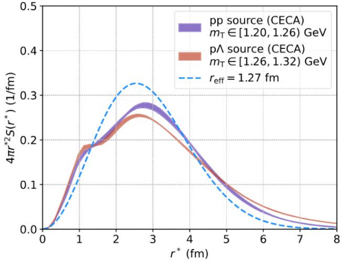
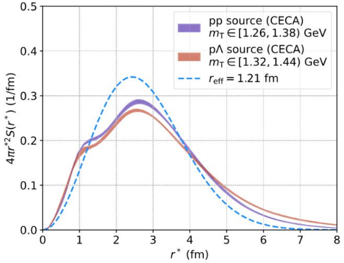
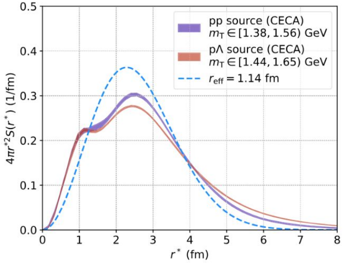
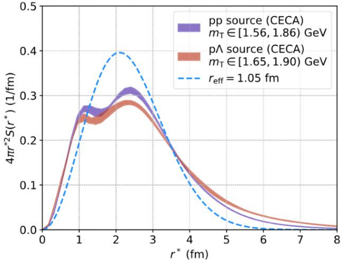


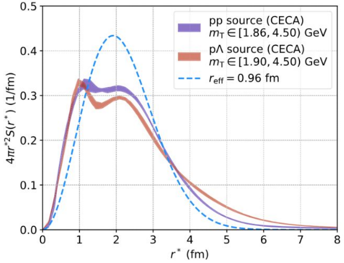


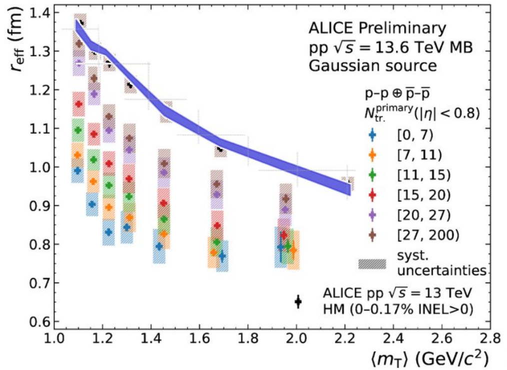


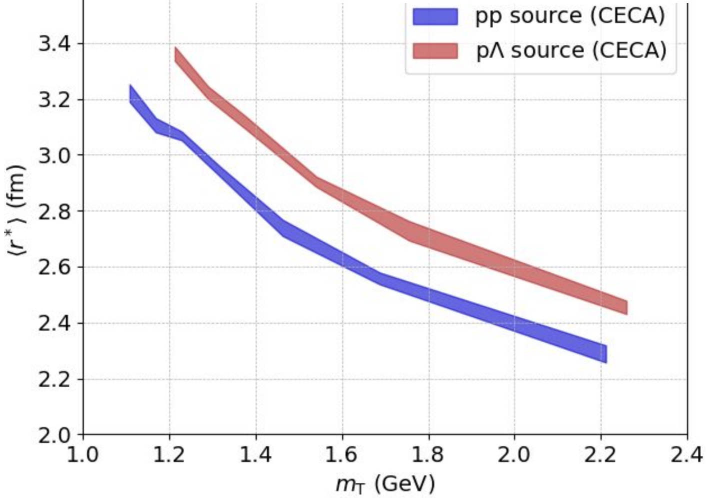






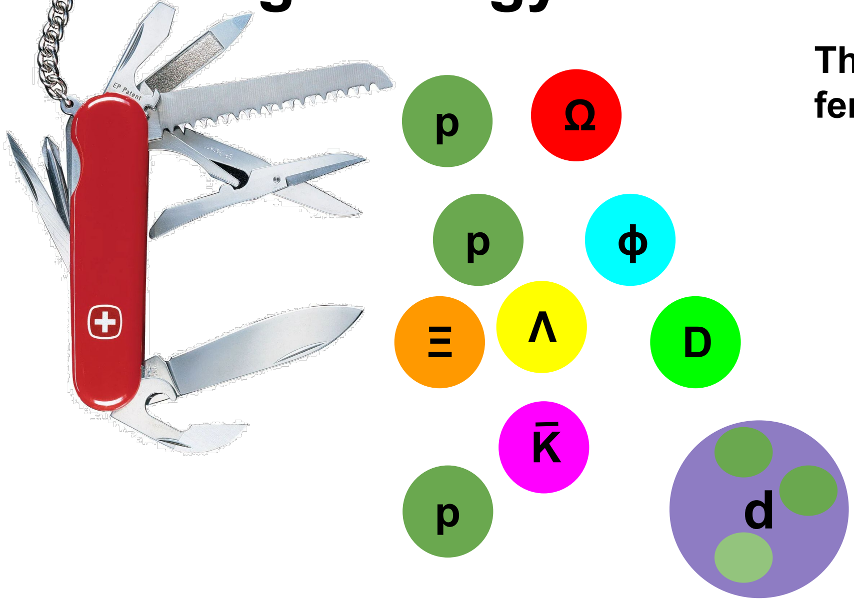






And so much more was done !

Low energy scattering experiments in high energy collisions @ ALICE



The exhaustive list of recent ALICE femtoscopy measurements

PRC 99 (2019) 2, 024001	p–p, p–Λ, Λ–Λ (methods)
PLB 797 (2019), 134822	Λ–Λ
PRL 123 (2019), 112002	p–Ξ
PRL 124 (2020) 092301	p–K
PLB 805 (2020), 135419	p–Σ0
PLB 811 (2020), 135849	p–p, p–Λ
Nature 588 (2020) 232-238	p–Ξ, p–Ω
PRL 127 (2021), 172301	p–ϕ
PLB 822 (2021) 136708	p–K
PRC 103 (2021) 5, 055201	Λ–K
PLB 833 (2022), 137272	p–Λ
PLB 829 (2022), 137060	baryon–(anti)baryon
PRD 106 (2022) 5, 052010	p–D
PLB 833 (2022) 137335	K0–K0, Kch–K0
PLB 844 (2022), 137223	Λ–Ξ
EPJA 59 (2023) 7, 145	p–p–p, p–p–Λ
EPJA 59 (2023) 12, 298	p–p–K
EPJC 83 (2023) 4, 340	p–K
PLB 845 (2023), 138145	Λ–K
PRX 14 (2024) 3, 031051	p–d, K–d

And so much more was done !

Low energy scattering experiments in high energy collisions @ ALICE

Small collision systems from ALICE @ the WPCF

Novel constraints for the multi-strange meson-baryon interaction using correlations
by Oton Vazquez Doce, Tue @ 9:00

Accessing the strong interaction in three-hadron systems via proton-deuteron femtoscopy
by Bhawani Singh, Wed @ 14:10

Chiral symmetry restoration studies with Femtoscopy
by Maximillian Korwieser, Thu @ 15:55

Demystifying the interior of neutron stars with femtoscopy at ALICE
by Marcel Lesch, Fri @ 13:55

exhaustive list of recent ALICE oscopy measurements

PRC 99 (2019) 2, 024001	**p–p, p–Λ, Λ–Λ (methods)**
PLB 797 (2019), 134822	**Λ–Λ**
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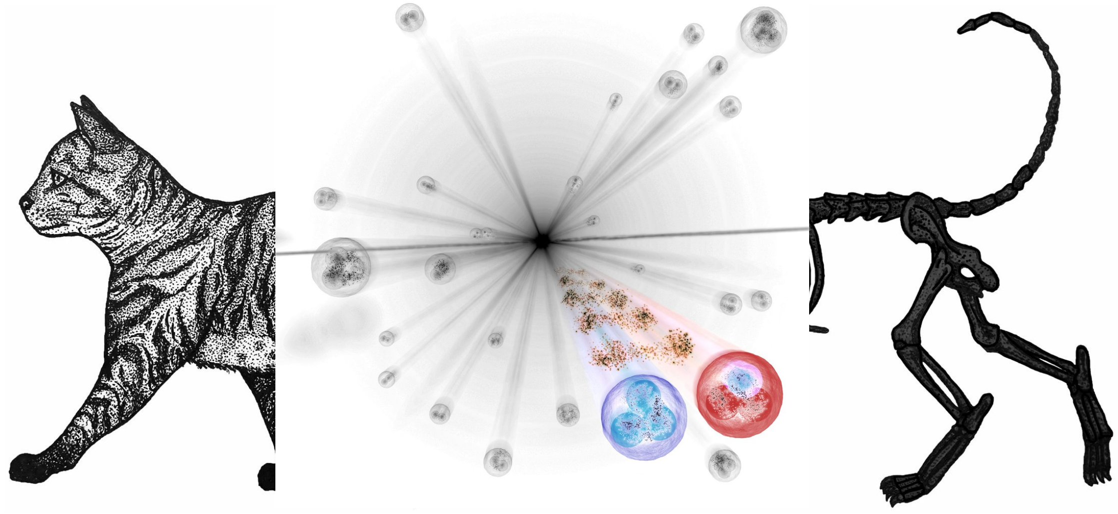
PLB 811 (2020), 135849	**p–p, p–Λ**
Nature 588 (2020) 232-238	**p–Ξ, p–Ω**
PRL 127 (2021), 172301	**p–ϕ**
PLB 822 (2021) 136708	**p–K**
PRC 103 (2021) 5, 055201	**Λ–K**
PLB 833 (2022), 137272	**p–Λ**
PLB 829 (2022), 137060	**baryon–(anti)baryon**
PRD 106 (2022) 5, 052010	**p–D**
PLB 833 (2022) 137335	**K0–K0, Kch–K0**
PLB 844 (2022), 137223	**Λ–Ξ**
EPJA 59 (2023) 7, 145	**p–p–p, p–p–Λ**
EPJA 59 (2023) 12, 298	**p–p–K**
EPJC 83 (2023) 4, 340	**p–K**
PLB 845 (2023), 138145	**Λ–K**
PRX 14 (2024) 3, 031051	**p–d, K–d**

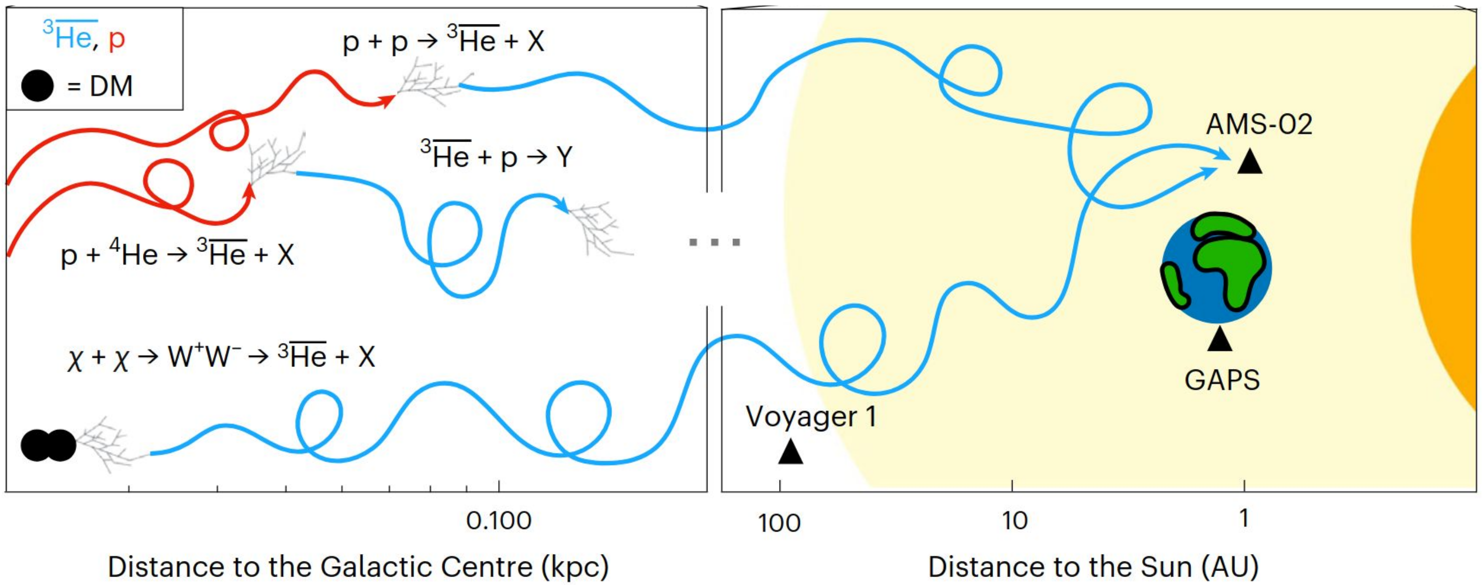
Part 2: Connecting femtoscopy and coalescence



Coalescence studies for light nuclei

Motivation: Indirect search for dark matter

ALICE Coll, [Nature Physics](#)
volume 19, pages 61–71 (2023)

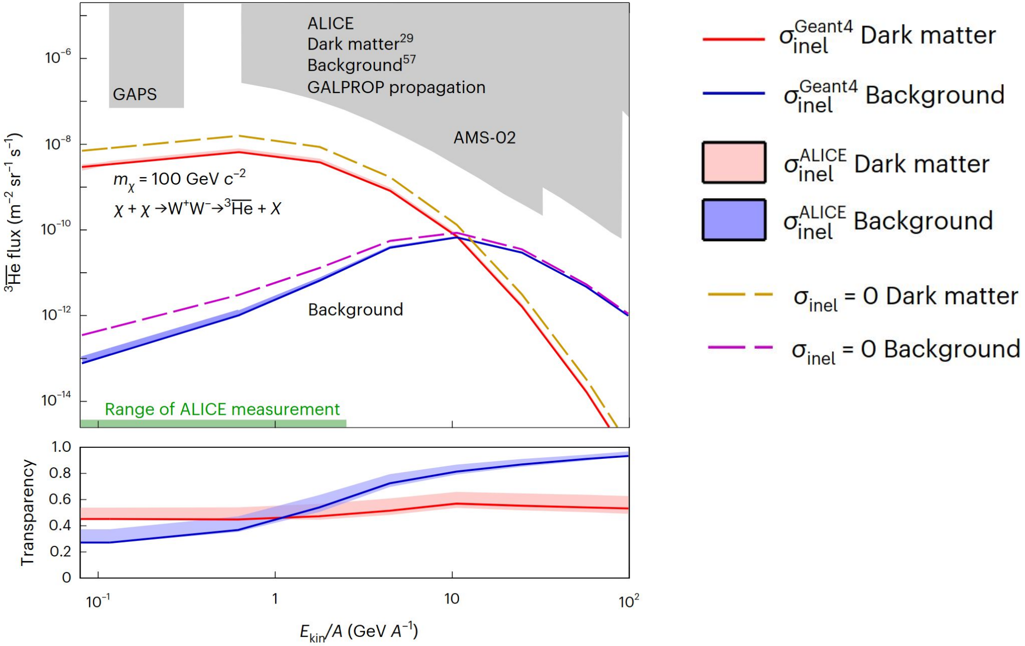


- Antinuclei cosmic rays: possible “smoking gun” signature of dark matter
- Essentially free of **astrophysical background**
- **Calculations require antinuclei production**/annihilation

Coalescence studies for light nuclei

Motivation: Indirect search for dark matter

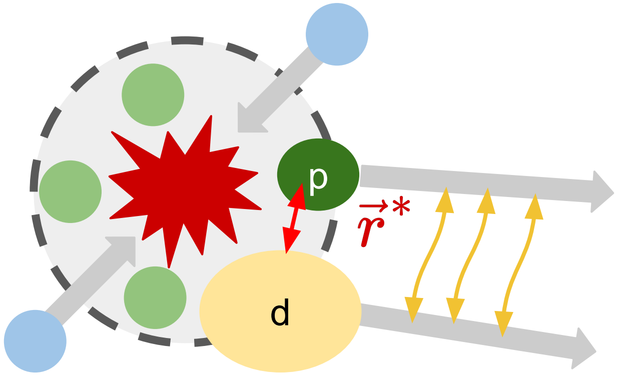
ALICE Coll, *Nature Physics* volume 19, pages 61–71 (2023)



- Antinuclei cosmic rays: possible “smoking gun” signature of dark matter
- Essentially free of **astrophysical background**
- **Calculations require antinuclei production**/annihilation

Femtoscopy @ LHC

p-d correlations

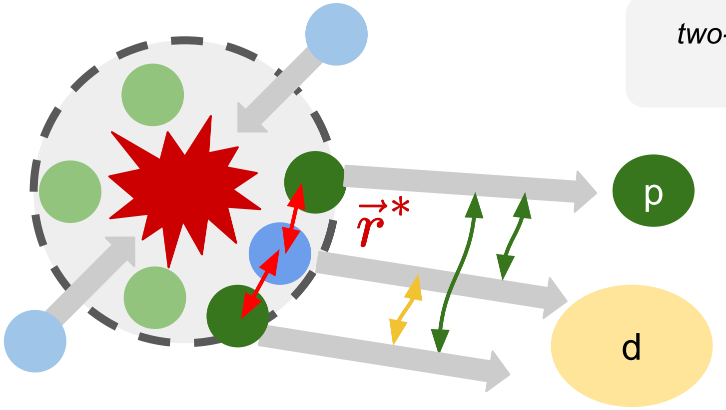


two-particle relative momentum
$q = 2 \cdot k^*$

Femtoscopy @ LHC
p-d correlations

Bhawani Singh, Wed @ 14:10

ALICE Coll., PRX 14 (2024) 3, 031051



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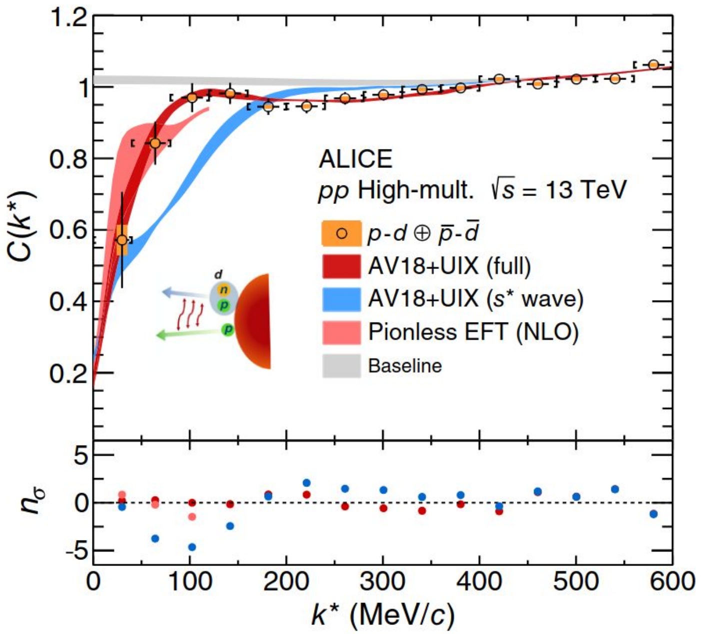
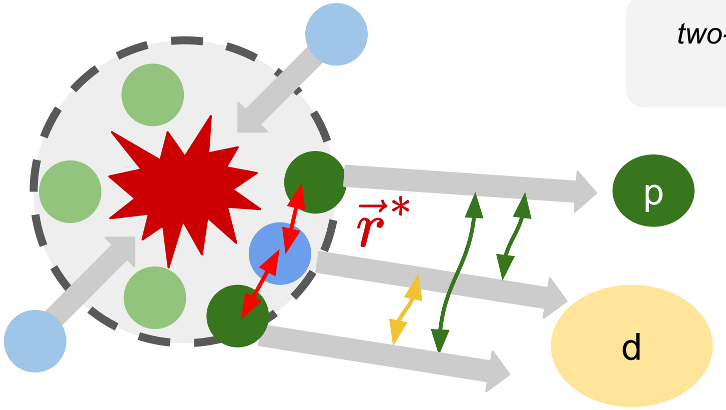


- Treating the system as three-body, including wave function symmetrization, works!
  Kievsky et al. PRC 108 (2023) 6, 064002
- **The potential used is AV18**.
- N.B. Genuine three-body forces are not required, <4% precision needed to probe them.

Coalescence @ LHC

Light nuclei formation



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Coalescence model:

- Nucleons close in phase space
  => possibility to coalescence
- Coalescence parameter B_A
  => probability for the nucleons to coalesce

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

Coalescence @ LHC

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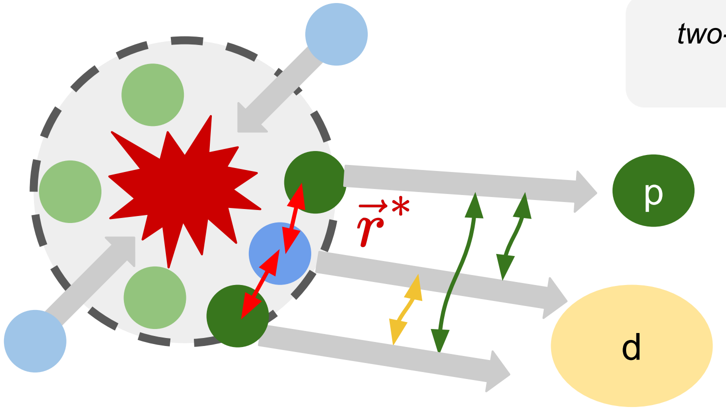

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- *Simple coalescence* models assume that nucleons coalesce if their k* is below a threshold p_0

Coalescence @ LHC

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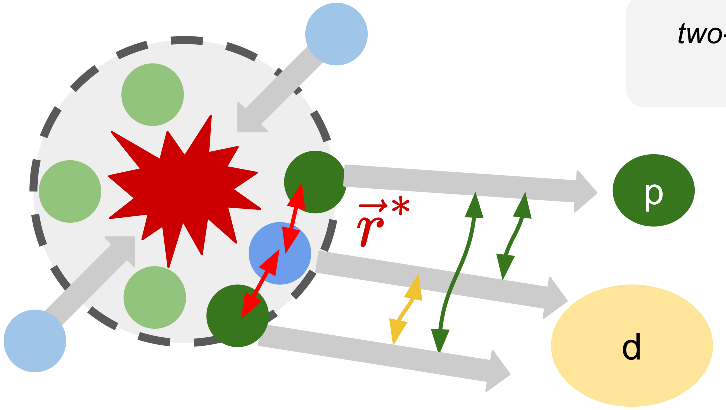

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$$\mathcal{P}(q, \sigma) = \frac{S_2}{(2\pi)^3 \sigma^6} \int d^3 r_p d^3 r_n \mathcal{D}(q, r) e^{-\frac{r_p^2 + r_n^2}{2\sigma^2}}$$

$$= \int d^3\zeta \, \Psi(\vec{r} + \vec{\zeta}/2) \Psi^*(\vec{r} - \vec{\zeta}/2) \exp(i\vec{q} \cdot \vec{\zeta})$$

$$= \frac{1}{(2\pi\sigma^2)^3} \exp\left(-\frac{\vec{r}_n^2 + \vec{r}_p^2}{2\sigma^2}\right)$$

Nucleus wave function

Relative momenta of the nucleons

Source size

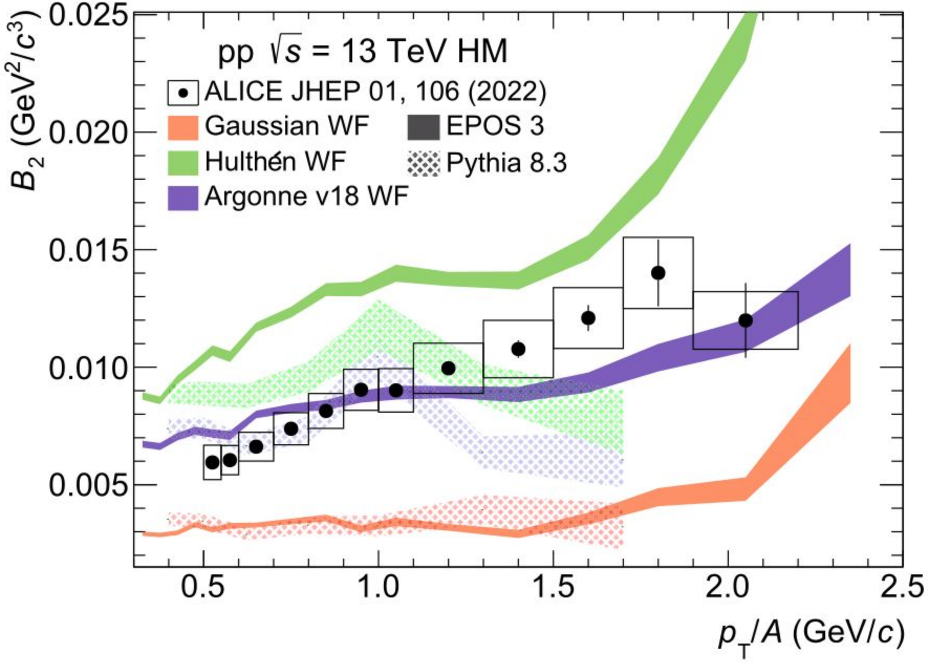
- *Simple coalescence* models assume that nucleons coalesce if their k* is below a threshold p_0
- *Advanced coalescence* models make use of quantum mechanical treatment, via the **Wigner formalism**

M. Kachelrieß, EPJA 56 (2020)

Mahlein et al., EPJC 83 (2023) 9, 804

Coalescence studies for light nuclei

B_2 measurements vs predictions (pp collisions)

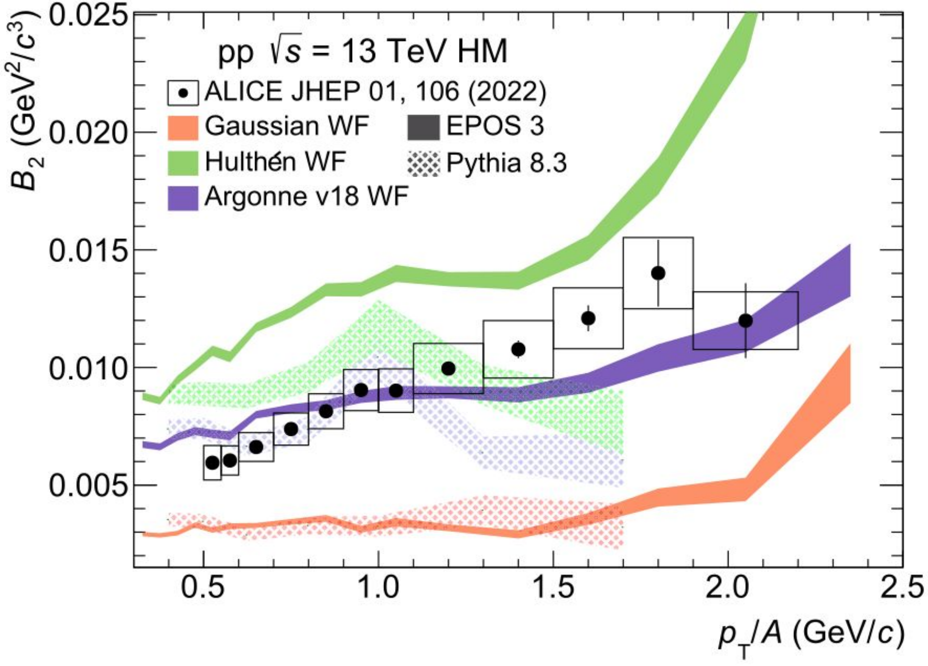


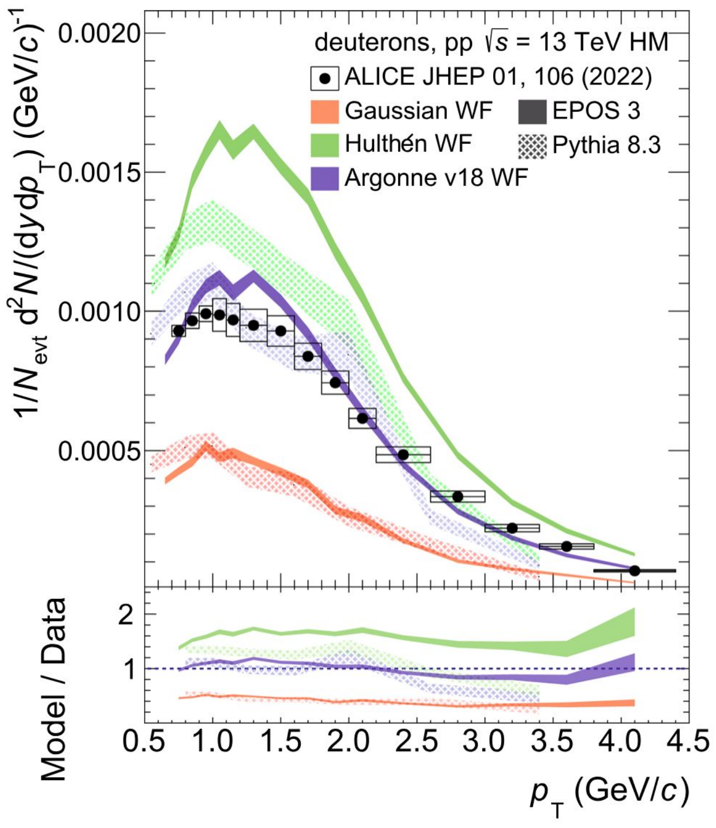
[Mahlein et al., EPJC 83 (2023) 9, 804]

- The $B_2(p_T)$ is reproduced using the Wigner formalism
- The **Argonne V18** potential used to evaluate the deuteron wave function can describe both p-p and p-d correlations
- The **source size** is taken from **p-p correlations**

Coalescence studies for light nuclei

pT spectrum reproduced as well!

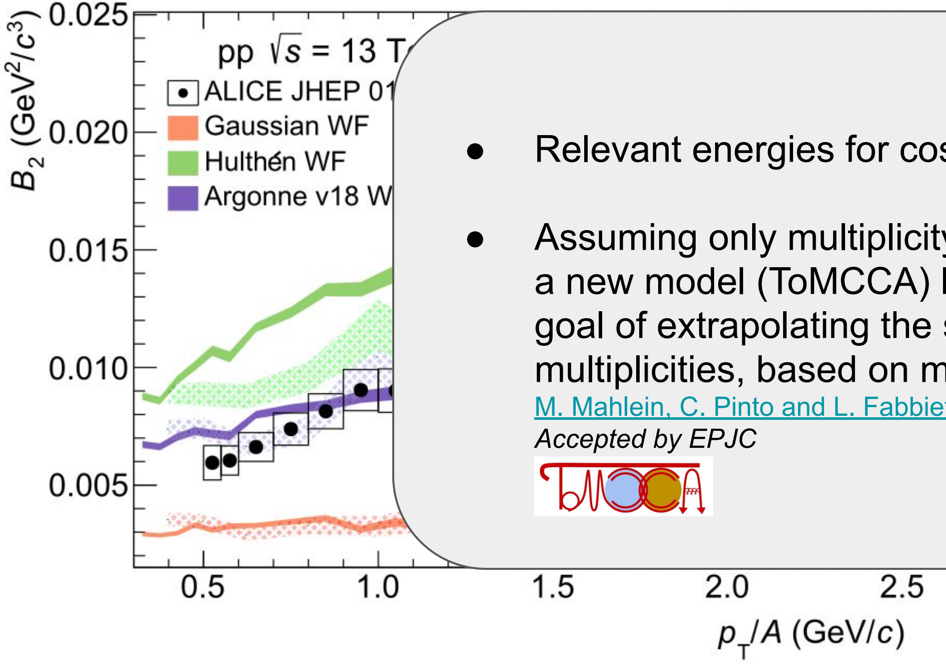


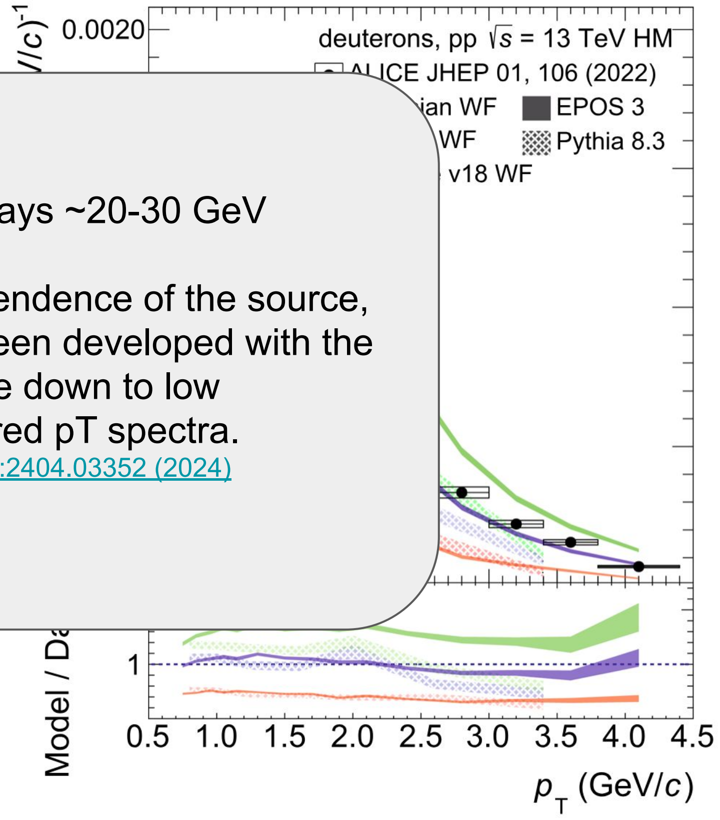


[Mahlein et al., EPJC 83 (2023) 9, 804]

Going forward

ToMCCA





- Relevant energies for cosmic rays ~20-30 GeV
- Assuming only multiplicity dependence of the source, a new model (ToMCCA) has been developed with the goal of extrapolating the source down to low multiplicities, based on measured pT spectra.
  [M. Mahlein, C. Pinto and L. Fabbietti, arXiv:2404.03352 (2024)](https://arxiv.org/abs/2404.03352)
  Accepted by EPJC

[*Mahlein et al., EPJC 83 (2023) 9, 804*]

A summary

And thank you for your attention!

- A common source in small collision systems allowing to study the FSI with high precision using femtoscopy

- Advancements in the source modelling

- Femtoscopy and coalescence can relate the emission source to momentum distributions of light nuclei

A teaser as an outlook:

- Some very interesting new developments related to πd correlations, relevant for the coalescence sturdies.
  Will trade details for drinks over dinner!